**Translator's Preface**

Reprint from: Meeting of the Swiss Natural Sciences Society,
Lucerne 1924. II$^{e}$ Part, S. 85-93

# Concerning the Aether

This paper seems only to have come to light when it came up for sale, with a substantial number of other works by Einstein, at Christie's Online Sale 30 October – 7 November 2019. It was possible to download an offprint of the original paper which is translated below. This was the property of H.A. Einstein at Berkeley, one of Einstein's sons.

Comments on the translation are, of course, welcome.

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19 February, 2020

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Lucerne 1924. II$^e$ Part, S. 85-93

# Concerning the Aether

Lecture delivered on the 105th Yearly Meeting of the Swiss Natural Sciences Society in Lucerne, on 4 October 1924

by

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While the subject here is Aether, it should not, of course, be taken to be about the physical Aether of mechanical wave theory which is based on Newtonian Mechanics, and which concerns simply the velocity of the individual points. In my opinion, this theoretical construction's role has finally been played out due to the establishment of the special theory of relativity. This concerns more generally those things which are thought to be physically real and which, in addition to the ponderable matter consisting of electrical elementary particles, play a role in the causal nexus of physics. Instead of "Aether" one might just as well speak of "physical qualities of space". Now, however, it could be argued that all objects of physics fall under this concept, because according to the rigorous field theory also ponderable matter, for example elementary particles, are to be conceived as constituting "fields" of a special kind, for example as special "space states". However, it will have to be admitted that in the present state of physics such a conception would be premature, for so far all the efforts of the theoretical physicists aimed at this end have failed. Thus, in the current state of affairs, we are virtually forced to distinguish between "matter" and "fields", but we may hope that later generations will overcome this dualistic conception and replace it with a unified one, as field theory has tried in vain in our day.

It is usually believed that Newtonian physics was unaware of an Aether, rather it was only the undulation theory of light that introduced an omnipresent medium that determined the physical phenomena. This of course is not the case. Newton's mechanics has its "Aether" in the sense indicated, which however is called "absolute space". In order to clarify this, and at the same time to somewhat sharpen the concept of the Aether-term, we must step back a bit.

We consider first a branch of physics that manages without Aether, namely Euclidean Geometry, which was conceived as the theory of the possible ways of arranging essentially rigid bodies so that they are in contact with each other. (We ignore the rays of light that may also be involved in the formation of the terms and laws of geometry.)

The positioning laws of solid bodies with the exclusion of relative movements, temperatures and deformation influences, as idealized in Euclid's geometry, work with the concept of the rigid body; any environmental influences that are thought to be independent of the bodies and thought to act on the bodies and influence their laws of arrangement are not known to Euclidean geometry. The same applies to non-Euclidean geometries of constant curvature, if these are viewed as (conceivable) body-arrangement laws of nature. It would be different if we were to assume a geometry of variable curvature; this would mean that the possible contact points of essentially rigid bodies in different cases would be different, and caused by environmental influences. Here, in the sense of our consideration, one would have to say that such a theory makes use of an Aether hypothesis. Its Aether would be something physically real, as good as matter. If the laws of arrangement were not influenced by physical factors, such as accumulation and state of motion of bodies in the environment, etc., then this Aether would be called "absolute" (i.e. independent of influences of any other objects).

Just as little as Euclidean (physically interpreted) geometry needs an Aether, so just as little does kinematics or phoronomy need classical mechanics or something similar; its propositions have a clear physical meaning if it is only assumed that the influences of motion on scales and clocks, as assumed in special relativity, do not exist.

Other matters in Galileo's and Newton's Dynamics: The Law of Motion "Mass $*$ Acceleration = Force" contains not only a statement about material systems, not even if, as in Newton's fundamental law of astronomy, that the force is expressed by distances, and by sizes, the real definition of which can be based on measurements with rigid measuring bodies. The real definition of acceleration cannot be based entirely on observations of rigid bodies and clocks. It cannot be referred back to the measurable distances between the points constituting the mechanical system. For their definition one needs a coordinate system, for example reference bodies of appropriate states of motion. If the state of motion of the coordinate system is chosen differently, the Newtonian equations are not valid in relation to it. In those equations the milieu in which the bodies are moved implicitly appears as a real factor in the laws of motion in addition to the real bodies and their distances that can be defined by measuring bodies. In Newton's kinematics, "space" has physical reality — in contrast to geometry and kinematics. We wish to call these physically real entities, which enter into the Newtonian law of motion in addition to the observable ponderable bodies, the "Aether of mechanics". The occurrence of centrifugal effects in a (rotating) body whose material points do not change their distances from one another shows that this Aether appears not just as a fantasy of Newtonian theory, but as something real in nature that corresponds to it.

We see that for Newton, "space" was something physically real, in spite of the strangely indirect way in which this "real" comes to our knowledge. Ernst Mach, who first after Newton, undertook a deep analysis of the foundations of mechanics, clearly recognized this. He sought to escape the hypothesis of the "Aether of Mechanics" by attempting to reduce the inertia to an unmediated interaction between the envisaged mass and all other masses in the world. Although this conception is logically possible, it is for us today, as a long-distance effect theory, no longer seriously considered. The mechanical Aether, designated by Newton as "absolute space", must therefore be regarded by us as a physical reality. Of course, however, the term "Aether" must not lead one to think like the physics of the 19th century which considered it somewhat analogous to ponderable matter.

When Newton described the realm of physics as "absolute", he also thought of it as having another property which we here call "Aether". Every physical object affects others and conversely is generally influenced by others. But this latter does not apply to the Aether of Newtonian Mechanics. The inertia-giving property of the latter cannot be influenced by classical mechanics, neither by the configuration of matter nor by anything else; insofar it can be described as "absolute".

It became clear to physicists only in recent years that the preference for inertial systems over non-inertial systems requires that a real object be provided as the cause. Historically, the Aether hypothesis in its present form evolved through sublimation from the mechanical Aether hypothesis of optics. After long, fruitless, efforts, the conviction arose that light was not to be understood as a movement of an inertial, elastic medium, and that the electromagnetic fields of Maxwell's theory could not at all be interpreted as mechanical. The electromagnetic fields were thus, under the pressure of these failures, gradually, in the end, regarded as irreducible physical realities not to be explainable as states of the Aether. What still remained of the Aether from the mechanical theory was its certain state of motion; to some extent, its embodiment of an "absolute quiet". Objects in Newtonian mechanics are equal in all inertial systems. So it seemed from Maxwell-Lorentz's theory of the state of motion of an allowed coordinate system (at rest with respect to the Aether) to be completely determined. It was tacitly assumed that this preferred system was at the same time an inertial system, i.e. that the inertial principle applied relative to the electromagnetic Aether.

Also, physicist's fundamental view was modified in a second way under the influence of the Maxwell-Lorentz theory. Following this theory, electromagnetic fields would be regarded as fundamental, irreducible, entities which seemed destined to rob the ponderable inertial mass of its fundamental importance in mechanics. It was concluded from Maxwell's equations that a moving electrically charged body is surrounded by a magnetic field whose energy is, to a first approximation, quadratically dependent on the velocity.

What could be more obvious than to consider all kinetic energy as electromagnetic energy? One could then hope that the mechanics could be traced back to the electromagnetics after the failure to trace the electromagnetic processes back to the mechanical ones. This seemed all the more hopeful, as it became more and more likely that all ponderable matter is composed from electrical elementary particles. In the meantime one could not overcome two difficulties. First, the Maxwell-Lorentz equations did not explain why the electric charge constituting an elementary electric particle can exist in equilibrium despite the electrostatic repulsive forces. Second, electromagnetic theory did not explain gravitation naturally and satisfactorily. Nevertheless, the successes that electromagnetic theory has brought to physics have been so significant that it has been regarded as the most secure possession of physics, indeed as its most well-founded achievement.

Finally, Maxwell-Lorentz's theory influenced our attitude to the questions of the theoretical foundation that led to the establishment of the special theory of relativity. It was recognized that the electromagnetic equations do not in fact characterize any particular state of motion, but that according to these equations as well as classical mechanics, an infinite variety of coordinate systems moving uniformly against one another are equally justified if one only uses suitable transformation formulas for the spatial coordinates and for the time. It is well known that this knowledge resulted in a profound modification of kinematics and dynamics. The Aether of electrodynamics was no longer attributable to any particular state of motion. It did only — like the Aether of classical mechanics — not cause the preference of a certain state of motion, but only the preference of a certain state of acceleration. Therefore, one could no longer speak of simultaneous states at various points of the Aether in an absolute sense, the Aether was as if it were four dimensional, because there was no objective order of its states due to time alone. Also, according to the special theory of relativity, the Aether was absolute, because its influence on inertia and light propagation was thought to be independent of physical influences of any kind. While in classical physics body geometry is assumed to be independent of the state of motion, according to the special theory of relativity the laws of Euclidean geometry for the arrangement of relatively mutually resting bodies only apply if these bodies are at rest relative to an inertial system;[1] this can be easily deduced from the so-called Lorentz contraction. Therefore body geometry like dynamics are also conditioned by the Aether.

The general theory of relativity eliminates a problem of classical dynamics: according to the latter inertia and gravity appear as quite different, mutually independent, phenomena even though they are both conditioned by the same physical constant, the mass. The theory of relativity overcomes this defect by defining the dynamic behavior of the electrically neutral mass point by the law of the geodesic line, in which the inertial and gravitational effects are no longer distinguished. In doing so, it adds to the Aether point-to-point variable properties that determine the metric and the dynamic behavior of material points, which in turn are determined by physical factors, namely by the distribution of mass and/or energy. The Aether of the general theory of relativity thus differs from that of classical mechanics or of the special theory of relativity in that it is determined not as "absolute", but, due to its locally variable properties, by the ponderable matter. This determination is then complete if the world is spatially finite and self-contained. That it is not preferred in the general theory of relativity, where there are spatio-temporal coordinates clearly linked to the metric, is more due to the mathematical form of this theory than to its characteristic physical content.

Even with the application of the formal apparatus of the general theory of relativity, it was not possible to attribute all inertia to electromagnetic fields, nor any other fields. Also, in my opinion, we have not gotten beyond a superficial classification of the electromagnetic forces into the scheme of general relativity. The gravitational and inertial phenomena co-determining the metric tensor on the one hand and the tensor of the electromagnetic field on the other hand, still appear as essentially different expressions of the Aether state, the logical independence of which is more likely to be due to the incompleteness of our theoretical construction than to that of a complex structure of reality.

To be sure, Weyl and Eddington have found, by generalizing Riemann geometry, a mathematical system which makes both types of field appear united under a single point of view. But the simplest field theories that each theory provides do not seem to me to be advances of physical knowledge. In fact, it seems today that we are much further away from a knowledge of electromagnetic laws than seemed to be the case at the beginning of this century. To justify this opinion, I would like to briefly mention the *Problem of the magnetic Earth- and Solar-field* as well as the *Problem of Light Quanta*, which to a certain extent concerns problems of the coarse structure and the fine structure of the electromagnetic field.

The Earth and Sun have magnetic fields whose orientation and meaning are closely related to the rotation axes of these celestial bodies. According to Maxwell theory, those fields could result from electric currents flowing opposite to the rotational movement about the axis of rotation of the celestial bodies. Also, by analog, the sunspots, which are with good reason regarded as a vortex, have very powerful magnetic fields. However, it is hardly conceivable that in all these cases electrical conduction or convection currents of sufficient strength are really present. On the contrary, it looks as if cyclic movements of neutral masses produce magnetic fields. Neither Maxwell's theory in its original form nor the advanced form of the theory in terms of the general theory of relativity can predict the generation of such a field. Here, it seems to us that nature points to a fundamental, as yet undetected, theoretical connection.[1]

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[1] For bodies which are at rest relative to each other, but in their total rotating against an inertial system, do not (according to the special theory of relativity) give, for example, Euclidean Geometry.

If it were just the case that field theory in its present form does not appear to be developed, then the facts and thoughts summarized in *quantum theory* threaten to blow up the foundation of field theory altogether. The arguments that photons of light are conceived as physical realities are increasing, and thus that the electromagnetic field cannot be regarded as the ultimate reality to which the other physical objects could be attributed. After the theory of Planck's formula had already shown that the transmission of energy and momentum by radiation takes place as if the latter consisted of atoms moving with the speed of light $c$ of energy $h\nu$ and momentum $\frac{h\nu}{c}$, Compton's experiments on the scattering of X-rays on matter demonstrated that scattering events occur in which some light quanta encounter electrons and these transfer to them a part of their energy, thus changing the light quanta's energy and direction. At least the fact is that the X-rays show (as Debye and Compton have shown) frequency changes due to their dispersion, as required by the quantum theory.

A recent work by the Indian Bose on the derivation of Planck's formula has also appeared, which is of particular importance for our theoretical view for the following reason: So far, all the derivations of Planck's formula have somehow made use of the hypothesis of the undulation structure of radiation. Thus, for example, the factor $\frac{8\pi h\nu^3}{c^3}$ in this formula was obtained from the known Ehrenfest-Debye derivative by counting the number of natural oscillations of the cavity which belong to the frequency range $d\nu$. Bose replaces this enumeration based on the concepts of undulation theory with a gas-theoretical calculation, in which he refers to a quantum of light considered to be in the form of a molecule in the cavity. This raises the question of whether or not the diffraction and interference phenomena could be connected to quantum theory in such a way that the field-like theoretical concepts are only expressions of the interactions between quanta, whereby the field is no longer attributed to an independent physical reality.

The important fact that according to Bohr's theory the frequency of the emitted radiation is not determined by electrical masses which go through periodic processes of the same frequency can only reinforce us in our doubt about the independent reality of the undulation field.

But even if these possibilities mature into real theories, we will need the Aether, i.e. a continuum equipped with physical properties, which theoretical physics cannot do without; because the general theory of relativity, on whose fundamental points of view physicists will probably always adhere, excludes an immediate remote effect; every near-impact theory, however, requires continuous fields, that is, also the existence of an "Aether".

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[1] Use of a close electrodynamic analogy helps to establish a relationship of the form $dh = -C\ dm\frac{[\upsilon, r]}{\gamma^3}$, where $dm$ is a mass $r$, moving with velocity $\upsilon$, and $\gamma = |r|$ is taken to be the distance of this point from the mass. (The formula can only at most apply for cyclic motion and as a first approximation.) Thus the correspondence between the solar magnetic field and the earth's electric field is correct to an order of magnitude. The constant $C$ is of dimension $\frac{\sqrt{\text{Gravitational}-\text{Constant}}}{\text{the speed of light}}$. From this we can conjecture the order of magnitude of the constant $C$. Setting this value in the above formula gives — applied to the rotating earth — the correct order of magnitude for the magnetic field of the Earth. These relationships deserve attention, but could be based on coincidence.